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MEASURED AND CALCULATED RADIATION LEVELS PRODUCED BY GALACTIC AND SOLAR COSMIC RAYS IN SST ALTITUDES AND PRECAUTION MEASURES TO MINIMIZE IMPLICATIONS AT COMMERCIAL SST-OPERATIONS

T. Foelsche, Rosalind Mendell*, Richard R. Adams,
and John W. Wilson

NASA Langley Research Center
Langley Station, Hampton, Va.

*New York University

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T. Foelsche, Rosalind Mendell,* Richard R. Adams, and John W. Wilson

NASA Langley Research Center
Langley Station, Hampton, Virginia

ABSTRACT

Recent estimates of dose equivalents as function of altitude produced by Galactic and Solar Cosmic Rays are presented. The dose equivalents of Galactic Cosmic Rays are derived from measurements during the years 1965-1968 in high latitude and altitudes up to 140,000 feet of biologically effective components such as energetic neutrons, tissue ionization and stars in tissue-equivalent material.

Attempts to measure the biologically important components or dose equivalents during intense and energetic solar events were not successful until the present time.

To encompass especially giant energy events as that of February 23, 1956, which are considered the most significant for commercial SST-operations, nucleon transport calculations have been made at Langley for primaries and secondaries up to 10 Gev using H. Bertini's secondary production cross sections to 2 GeV for O^{16} with semi-empirical extrapolation to 10 Gev.

In this way the build up of secondaries as observed for the high energy Galactic Cosmic Ray particles is obtained. For the February 1956 event only rough estimates of dose equivalents as a function of altitude were available before. The uncertainty of these doses is thus essentially reduced to the uncertainty in the primary spectra. The new calculations are compared with previous calculation of M. Leimdorfer, R. G. Alsmiller, and F. T. Boughner for low energy events, which were made with Bertini's secondary production cross sections for primaries up to 450 MeV.

*Assistant Director, Cosmic Ray Department, New York University.

Results of the measurements and calculations, which approach upper limits of earlier estimates, are:

(1) The crew dose equivalent averaged over the highly active solar cycle 19 (1954-1964) from Galactic and Solar Cosmic Rays at 40 hours/month in cruising altitude at high latitudes should have been ($\lesssim$ 20%) of the Maximum Permissible Dose rate of 5 rem/year established by the ICRP, if in the average 10 hours/week in cruising altitude is assumed. A percentage of 12% is due to Gal. C.R.

(2) The dose equivalent for occupants in cruising altitude in high latitude during the maximum phase of the February 1956 event should have been between 0.5 and 3 rem/hr. Such exposure without justifiable reasons might be considered unacceptable for pregnant occupants and may lead to forensic consequences, if no evasion measures or proof is provided, that the exposure did not surpass accepted levels.

Events of this kind, which may occur a maximum of one to two times per 11-year solar cycle are considered the most relevant radiation problem for commercial SST-operations, so far as known solar cosmic radiation is concerned. For other high intense and energetic events, of the solar cycle 19, only doses in the order of 10-50 m rem/hr are obtained. The efficiency, inferred from the calculations, of descent to lower altitudes in case of the February 1956 high energy solar event and means for minimizing implications for commercial SST-operations are discussed.

I. Introduction

To our present knowledge in SST-cruising altitudes ($\approx$ 60 - 68,000 feet, 18 - 21 km) are encountered mainly ionizing radiations produced by the energetic low level Galactic Cosmic Rays and transient Solar Cosmic Rays of lower energy, however, orders of magnitude higher intensity in some cases. The G a l a c t i c Cosmic Rays (Gal. C.R.) consist to roughly 85% of protons, 12% of α-particles and 3% of heavier nuclei of an average energy of 2-3 GeV/nucleon with particles extending to energies up to 10^{17} ev of decreasing intensity. The S o l a r Cosmic Ray (Sol. C.R.) primaries, also mainly protons and α-particles, have mostly only low energy up to 300 MeV or even up to 50 MeV, except for less frequent events in the medium energy range up to 2 GeV. In very rare cases as February 23, 1956 so called giant energy events were observed, with particles of up to 15 GeV energy of measurable intensity, indicating an astonishing potential of the sun to accelerate charged particles to high energies. Both, Galactic and Solar Cosmic Rays, produce at their penetration through the atmosphere a multitude of secondaries (protons, α, neutrons, heavy nuclei, γ-rays, mesons, and electron-photon cascades, which are in tissue in part more biologically effective than the primaries. The problem is to assess the biological weight or dose equivalent in tissue of this mixture of primaries and secondaries. The particles most unknown in their effects are the heavy primaries and energetic heavy nuclei produced in nuclear collisions of primaries with airatoms. These particles are highly rarified in SST-altitudes of today. More important, because of their much larger number, appear especially secondary energetic neutrons (0.1 - 400 MeV), which penetrate relatively freely in air produce, however, in tissue densely ionizing recoils and star prongs in nuclear collisions. There is furthermore star production in tissue from highly energetic charged primary and secondary protrons and α, even though they ionize along their path only lightly. These components and their products in tissue are of a more familiar nature and their effects are more comparable to the effects of lightly ionizing X-ray-produced electrons of higher dose. The X-ray dose equivalents are established by the ICRP for such particles and maximum permissible doses (MPD), to which the measured particles of different kind and the sum of their dose equivalents can be compared.

Theoretical studies and estimates of doses in SST-altitudes on the basis of available data are listed in references 1 - 14. The only measurements, known to these authors, of biological effective components in SST-altitudes except heavy primaries are those made by scientist of the University of Bristol for Galactic Cosmic Rays in tissue equivalent nuclear emulsions (ref. 15). Measurements of biological effective components during intense and energetic Solar Cosmic Ray events seem nonexistent.

To assist in the establishment of a position on operational requirement for commercial SST-operations, NASA-Langley has conducted since 1965 measurements of those biological effective components, which we consider most important (i.e., especially energetic neutrons, tissue ionization, and heavy primaries) at altitudes up to 137,000 feet with Balloons with cooperative assistance of the Office of Naval Research. Furthermore up to anticipated SST-altitudes, airplane flights were conducted with cooperative assistance of the A.F. Systems Command 1966, 1967 and since 1968, by mediation of FAA, with cooperative assistance of A.F. Chief of Operations, A.F. Weatherservice, and A.F. Weapons Laboratory in providing the opportunity for high altitude flights.

In section II, part of the balloon measurements on Galactic Cosmic Ray components during the first 4 years of the new solar cycle in high latitudes, and the resulting dose equivalents as functions of altitude are presented. From these measurements dose equivalents for the crew averaged over the entire solar cycle are estimated.

The airplane flights were especially designed to conduct latitude scans in SST-altitudes and to measure during solar events in high latitudes. Because of the low frequency of significant events, relevant data to check theoretical calculations may be expected only after several more years.

To assess theoretically the dose equivalent from Solar Cosmic Rays, since 1964 theoretical studies were conducted by the neutron division of Oak Ridge National Laboratories (Leimdorfer et al., ref. 9) and by NASA-Langley (refs. 6 and 11). A treatment of the most important "giant" energy events as that of February 1956 was not possible until recently. To achieve this a new transport code is developed by J. W. Wilson, NASA Langley (see Appendix II) and applied to this event, the most intense and energetic event of this kind observed since 1942 (see ref. 6).

The obtained dose equivalents as a function of altitude also for medium and low energy events are presented in section III. In the same section the average dose equivalent which would have been received by the SST-crew from all significant events of the highly active solar cycle 19 (1954-1964) is estimated. Special emphasis is given to the relative high exposure to crew and passengers, especially to pregnant occupants, received in a few hours if encountering the February 1956 event in its early phase in altitude and high latitude. Such event appears to be a major radiation problem relevant to SST-operations. From the calculations of dose equivalent as function altitudes the reduction of exposure at descending to different lower altitudes is obtained.

In section IV, the exposure of crew and passengers from Gal. and Sol. C.R. during cycle 19 is compared with the Maximum Permissible Doses for radiation workers and individuals of the general population, as established by the ICRP.

In section V, the dose equivalents as function of altitude in high latitudes and conclusions are summarized, which appear relevant to SST-operations. Precaution measures to minimize implications are discussed.

The instruments used in the NASA Langley program are:

(a) Phoswich scintillator-neutron spectrometer which measures the recoil proton fluxes in the range 1-10 MeV in 7 energy channels using the pulse shape discrimination principle. The instruments are designed by R. Mendell* who supervises also the calibrations, maintenance and reduction of data (n-flux 1-10 MeV, exponent of spectrum E^{-n}).

(b) Tissue equivalent Ion chambers, designed and built by AVCO, Tulsa, Oaklahoma, with the recorder part designed by R. R. Adams, NASA Langley who supervises the calibration, maintenance, and data reduction, the latter with Julia Goodwin.

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*NYU Cosmic Ray department, under direction of Prof. S. Korff.

(c) Large nuclear emulsion stacks** for obtaining a satisfactory statistics on the few heavy primaries and energetic heavy secondaries in a larger body, at SST-altitudes.

The balloon flight operations were supervised by R. Freeman of NASA Langley.

A brief explanation of the used terminology may be in order:

Particles more heavily ionizing along their path in tissue than X-ray produced electrons have higher biological effects, if the same energy per gram tissue is deposited. The energy absorbed/gr tissue is measured in rad $\left(1 \text{ rad} = \frac{100 \text{ erg}}{\text{g}}\right)$.

The ratio of rad doses of X-rays and heavier ionizing particles, respectively, which have roughly the same effects is called the Q_F factor (Quality factor of the particles) assumed here dependent only on the average specific ionization of the particles along their path (Linear energy transfer, "LET"). The higher rad dose of X-rays, which has the same effect as the smaller rad dose of the particles is called the (X-ray) dose equivalent or rem dose and is obtained by multiplying the actual rad dose of the particles with the Q_F factor; that is:

$$\text{rem (equivalent X-ray rad, dose equivalent)} = Q_F \times \text{rad-particles}$$

The relation between the LET of particles and the Q_F factors is established rough empirically and conservatively by the ICRP for protection guideline purposes. In these guidelines the Maximum Permissible Doses are given in rem.

To obtain the (X-ray) dose equivalent in rem, for example, of energetic neutrons, which produce in tissue heavily ionizing tracks like recoil protons (hydrogen content), heavy recoils, and low energy protons and α, evaporating after inelastic nuclear collisions with C,N,O and other atomic constituents of tissue, the LET-spectrum of these particles must be known.

The deposited energy per g tissue (rad) and the LET spectra in the considered g of a 30 cm thick tissue layer at normal and isotropic incidence are calculated with Monte Carlo methods for neutrons and protons of energies in the range 0.1 - 400 MeV in reference 17, reference 18, and reference 19, and presented in the form of flux to dose (to rad- and rem-dose) conversion factors. These conversion factors are used in all parts of the following paper to obtain from particle energy spectra of the environment dose equivalents and rad doses in small tissue samples (extremities) or in the depth of a body phantom. For neutrons in the energy range 0.1 - 10 MeV the flux to dose conversion factors agree about with those of Snyder-Neufeld published in Handbook 63, National Bureau of Standards, 1957. For evaporation particles the code of L. Dresner is used (ref. 20).

**The reduction of the data is still in progress.

II. The Galactic Cosmic Ray Dose Equivalents as Function of Altitude, Doses of Crew Averaged Over the Solar Cycle

In Figure 1 are plotted separately the different components of which the total dose equivalent is composed, as function of altitude and at different phases of the present solar cycle (1965 - 1968).

The plotted components derived from measurements are:

a. Tissue ionization in rad from all components, as ionization along the path of primaries and charged secondaries, from mesons, gamma rays, ionization produced by neutrons in tissue (i.e., of recoil protons, heavy recoils, neutron produced stars in tissue) and ionization due to stars produced by energetic charged particles all measured in the tissue equivalent ion chamber. Part of these components have, because of their high specific ionization, a Q-factor >1 which is taken into account separately in (b) and (c).

b. The difference of rem and rad dose produced by energetic neutrons (0.1 - 500 MeV) in tissue.

c. The difference of rem and rad dose of stars produced by primary and secondary charged particles in tissue.

To obtain the total dose equivalent (rem) by summation of parts (a), (b) and (c); the rad doses or energies deposited in tissue due to neutrons and charged particle-produced stars has been substracted from the total dose equivalents (rem) of neutrons and charged particle produced stars, since they are already measured in the tissue equivalent ion chamber.

The component (b) is obtained in the following way:
Only the flux and spectrum slope ($E^{-1.26}$) of neutrons in the energy range 1 - 10 MeV are measured with the neutron spectrometer. A substantial contribution to the total dose equivalent (and rad dose) of neutrons is due to neutrons of the lower energies 0.1 - 1 MeV (≈35%) and higher energies 10 - 500 MeV (≈23%). These contributions are calculated normalizing the spectrum of Newkirk (ref. 21) in the 0.1 - 1 MeV range and the spectrum obtained by J. W. Wilson in the high energy range ($E^{-1.2}$)* to the measured flux and spectrum between 1 and 10 MeV. To the total spectrum are applied the flux to dose conversion factors up to 60 MeV of D.C. Irving, R. G. Alsmiller and H. S. Moran (ref. 18) and W. E. Kinney and C. D. Zerby up to 400 MeV (ref. 17).

The component (c) or difference of rem and rad dose for stars was derived from measurements at different altitudes in tissue equivalent emulsions and calculations of P. J. N. Davison (ref. 15, "Star damage energy"). Since the total star damage energy (rem-rad dose) contains also the contribution of neutron produced stars, which is already taken into account in (b), for the contribution from charged particles the factor 1/2 is applied at high altitudes (65,000 - 110,000 ft.) and the factor 1/3 at 37,000 ft.

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*This exponent is approximately equal to the exponent of the spectrum of Hess, et. al., (ref. 22) in the energy range 10 - 400 MeV.

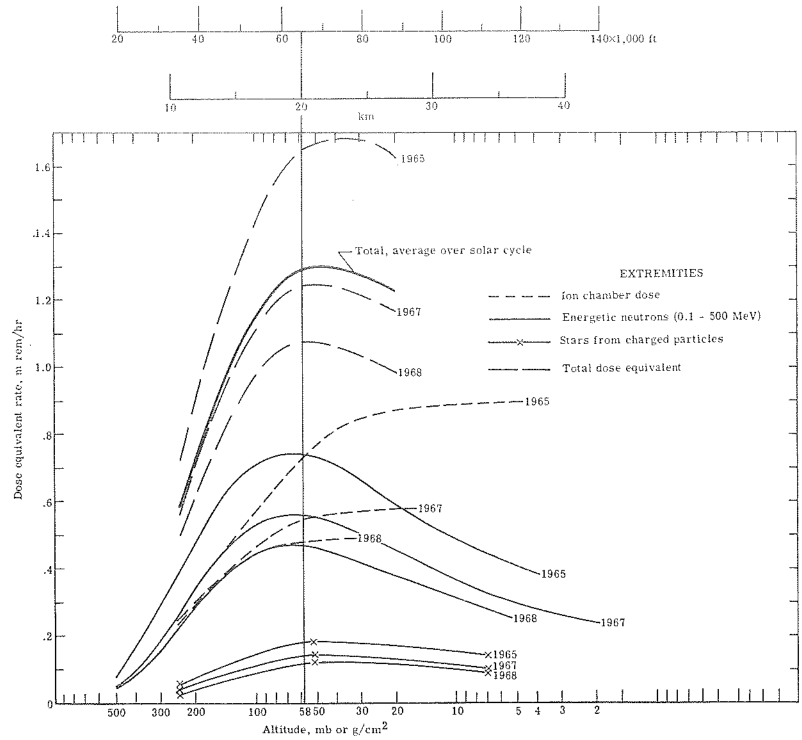

Figure 1.- Galactic Cosmic Ray dose equivalents for extremities (eyes, hands, ...) as function of altitude at different phases of the solar cycle.

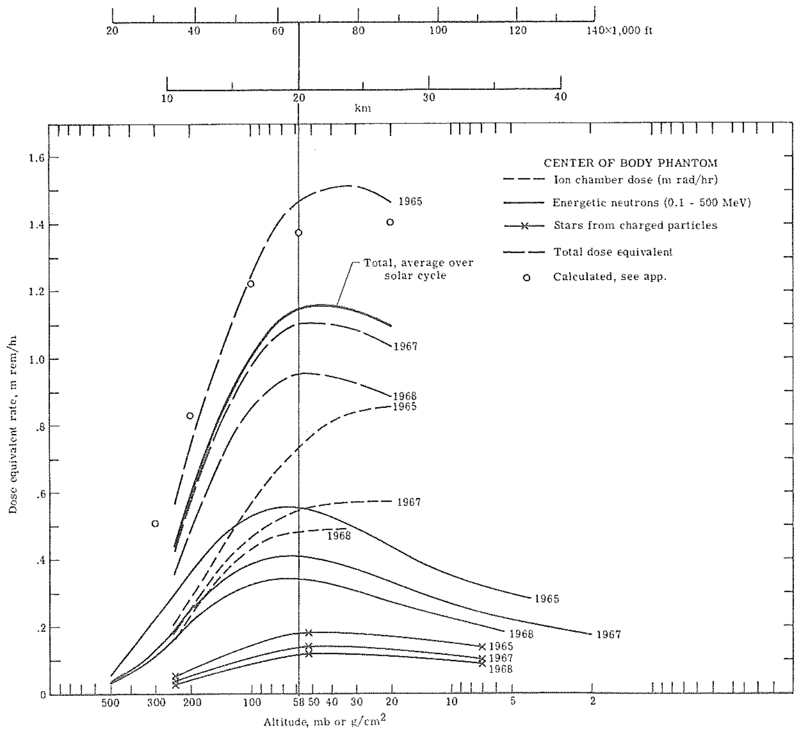

Figure 2.- Galactic Cosmic Ray dose equivalents for center of human body as function of altitude at different phases of the solar cycle.

The total dose equivalent in Figure 1 as function of altitude exhibits a peak at about 68,000 ft. (50 g/cm^2) also for the Galactic Cosmic Ray Maximum 1965 (about 1 year after Sunspot Minimum), which is due to the maximum neutron flux at this altitude as measured with the neutron spectrometer (See App. 1). The peak is not present in the ion chamber measurements (rad dose) for 1965. It may furthermore be noted, that the neutron damage dose (rem-rad) contributes about 50% to the total dose equivalent in these altitudes. The total dose equivalent of neutrons contributes even more.

The average dose equivalent over the solar cycle is obtained by multiplying those for 1965, 1967, and 1968, by 3, 4, and 4 years, respectively, and dividing by 11 years. At 65,000 ft. an average dose equivalent over the solar cycle of $1.3 \frac{\text{m rem}}{\text{hr}}$ (extremities) is obtained. This value is considered representative for extremities like hands, legs, and eyes. A small specimen of tissue or thin layer was considered in the calculations (first collision dose).

In figure 2, the dose equivalent in the center of a spherical body phantom is calculated on the basis of balloon measurement with n-spectrometer and ion chamber inside tissue equivalent phantoms (spherical shell of 15 g/cm^2 wall thickness of tissue equivalent material). The spectrum of neutrons 1 - 10 MeV was found significantly flatter within the phantom ($E^{-0.96}$) and the flux (E = 1 - 10 MeV) reduced, due to the moderating effect of the hydrogen containing material. The ion chamber values as function of altitude were essentially unchanged. In extending the spectrum to 0.1 MeV with the flatter spectrum and from 10 - 500 MeV with $E^{-1.2}$ as before, because neutrons E > 10 MeV are less slowed down at high energies, the average value: $1.15 \frac{\text{m rem}}{\text{hr}}$ in the center of of the body phantom is obtained. The dose equivalent in the center of the body phantom calculated using the neutron spectrum measured outside the phantom with the average flux to dose conversion factors (refs. 17 and 18) yields $1.12 \frac{\text{m rem}}{\text{hr}}$ in the center of the body phantom.

The circle symbols (O) in figure 2 are the average dose equivalents in a 30 cm thick tissue layer as function of altitude obtained by J. W. Wilson in exposing this body phantom to the nuclear cascade field produced by the Galactic proton spectrum at solar minimum, isotropically incident on top of the atmosphere. The agreement with the measured dose curve for Galactic Cosmic Rays is considered remarkable and an explanation for the flatter slope at low altitudes may be found in the fact that 40% of all Galactic nucleons are contained in α and heavy primaries, which are less prolific in production of energetic penetrating secondary nucleons. The α and heavy primaries are taken into account by a factor 1.4; i.e., 60% of their nucleons are treated as free protons (see discussion, appendix II).

Some samples of the measurements of energetic neutrons and tissue ionization in balloon flights in Fort Churchill are shown in Appendix I. The dose equivalents on the left scale take into consideration only neutrons 0.1 - 10 MeV and not 10 - 500 MeV. Furthermore the stars produced by charged particles in tissue are neglected.

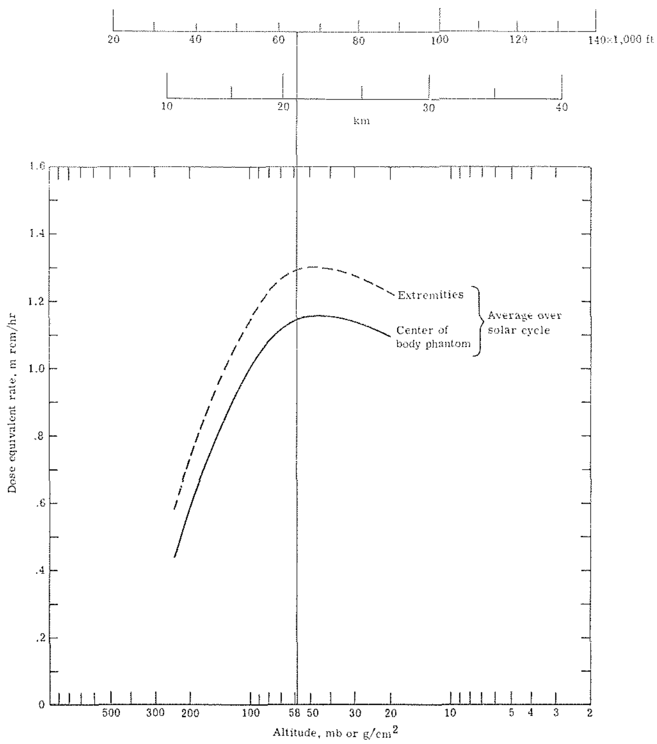

Figure 3.- Comparison of extremity and center of body dose equivalents averaged over the solar cycle.

In figure 3 the obtained average dose equivalents for extremities and center of body are compared. It may be noted that selfshielding of the body reduces the dose equivalent by only about 12% in SST altitudes, mainly due to moderation of neutrons.

As result from these measurements is thus obtained that the internal body dose for the crew averaged over the solar cycle at 40 hours/month or 10 hours/week in cruising altitude would be

$$1.15 \frac{\text{m rem}}{\text{hr}} \times 10 = 11.5 \frac{\text{m rem}}{\text{week}} \text{ (Galactic Cosmic Ray)}$$

or roughly 12% of the Maximum Permissible Dose equivalent for radiation workers (100 m rem/week, see also fig. 6 and Table II).

If a maximum time of 640 hours/year at altitude - 12.3 hours/week is assumed, the exposure of the crew would be 12% x 1.23 = 15% of the maximum permissible dose for radiation workers, which is by a factor 1.5 above the dose allowed for individuals of the general population.

III. Solar Cosmic Ray Produced Dose Equivalents as Function of Altitude

1. Dose equivalents during the events of February 23, 1956, and November 12, 1960, and comparison with previous estimates.

Figure 4 shows energy spectra characteristic for high (relativistic), medium- and low energy events on the basis of which the dose equivalents as function of altitude in Figure 5 are derived.

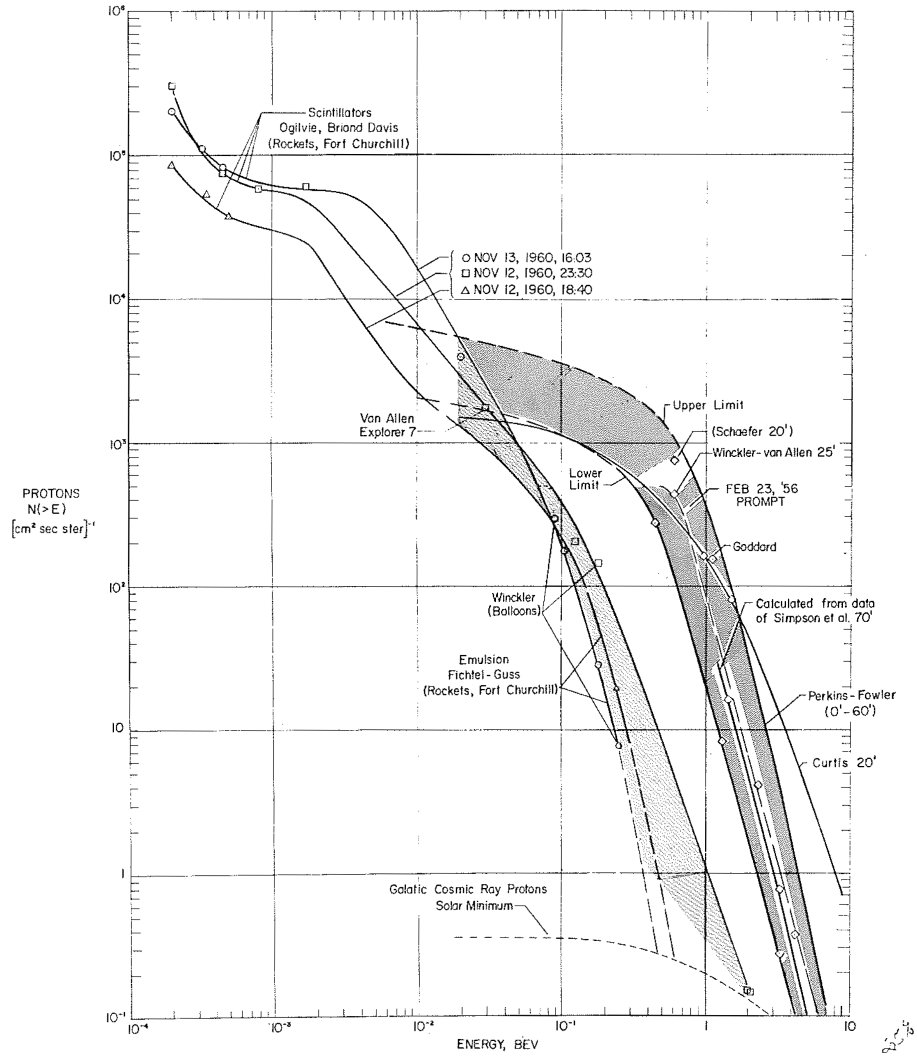

Figure 4.- Integral-flux energy spectra of extreme solar events. The prompt spectra of February 1956 were observed on different locations during the maximum phase of the event in the first hours after particle flux onset (composed from data cited in ref. 6 and ref. 7). The spectra of the November 12-13 event are observed 5 (1840 UT), 10 (2330 UT), 27 (1603 UT) hours after onset, respectively, (composed from data cited in ref. 6).

The data on the prompt spectra of February 1956 are incomplete especially in the energy ranges <1 GeV. The flux values depend also on the location of measurements. The particles arrived in the early maximum phase with their highest intensity in so-called impact zones. Two spectra, "upper" and "lower" limit in figure 4 which bracket the estimates of different authors, are chosen for the dose calculations. During solar cycle 19 (1954-1964) occurred one high energy event (February 1956); 3 medium energy events of extreme intensity (July 16, 1959; November 12 and 15, 1960) and 3 low energy events (May 12; July 10, 14, 1959) of extreme intensity.

In figure 5 the dose equivalents calculated according to Appendix II are compared with earlier estimates, reference 6 and reference 11, the latter based on reference 9 in which nuclear collisions or high energy primary and secondary nuclions (>450 MeV), respectively, have been treated as 450 MeV particles.

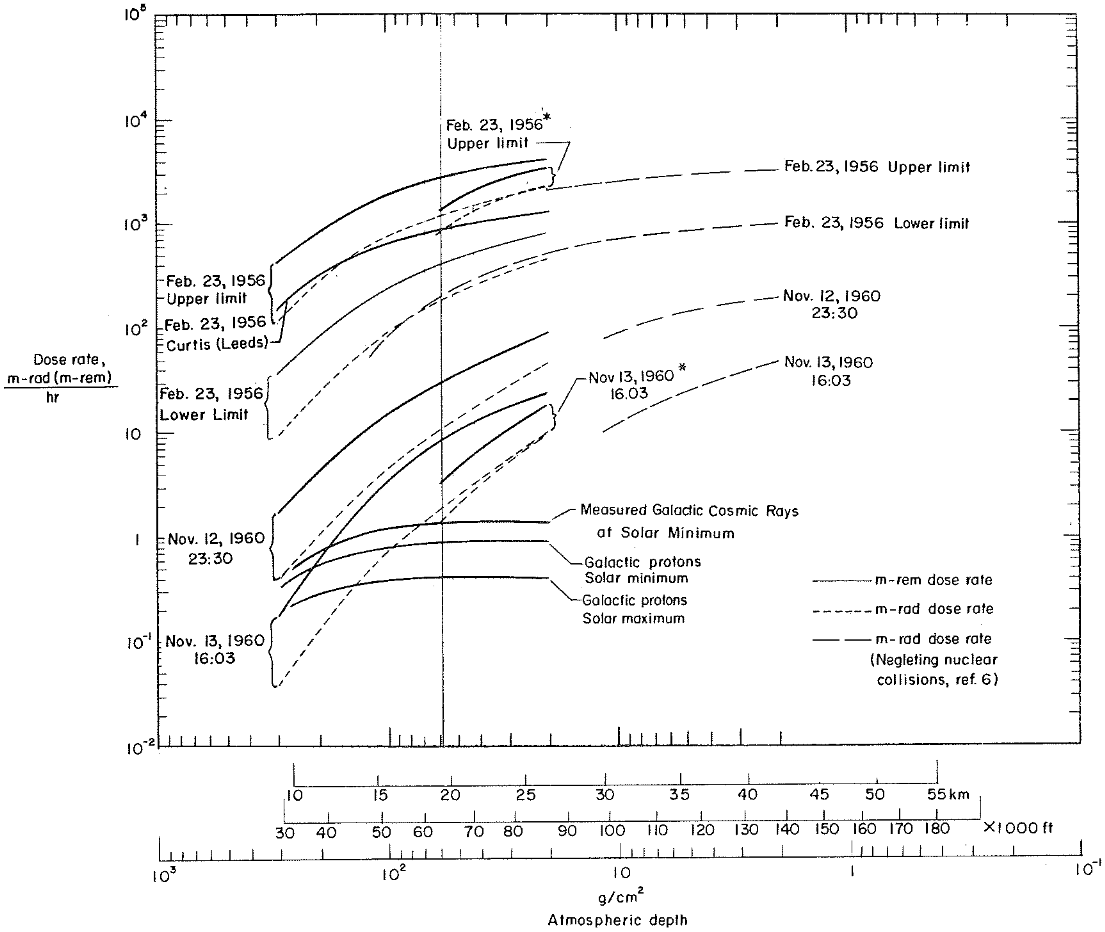

Figure 5.- Dose rates during the large solar events of February 23, 1956 (maximum phase), and November 12, 1960, at 1840, 2330, and 1603 (Nov. 13) universal time.

It may be noted in figure 5, that the biological effective components (dose equivalent) penetrate to considerably greater atmospheric depths than previously estimated. This is in large part due to the energetic neutrons (produced by high energy primaries and secondaries) which migrate freely deep into the atmosphere suffering occasional nuclear interactions, while the charged primary and secondary particles are slowed down by ionization (a detailed discussion is given in Appendix II). Furthermore, the dose equivalents in 65,000 feet are actually by about a factor 2 higher than estimated previously, in particular for the February 1956 event. The lower curves on galactic cosmic rays are calculated according to Appendix II from galactic cosmic protons only (solar maximum and minimum spectrum). From the comparison with the measured curve it may be concluded, that the calculations do not produce too high dose equivalents and reproduce the build up of secondaries realistically (Discussion App. II).

2. Exposure of the Crew from Solar Cosmic Rays

In figure 6 the dose equivalent received by a hypothetical crew during solar cycle 19 divided by 4800 flight hours in altitude is plotted. It is assumed in the computation that most major events of cycle 19 would have been encountered 2-4 times for 1 hour. The figure 4800 is the anticipated number of flight hours in cruising altitude in 10 years, which would accumulate, if the usual schedule of 80 flight hours per month is maintained and 40 hours/month are spent in cruising altitude. The obtained figure represents the average dose from solar cosmic rays per flight hour in altitude.

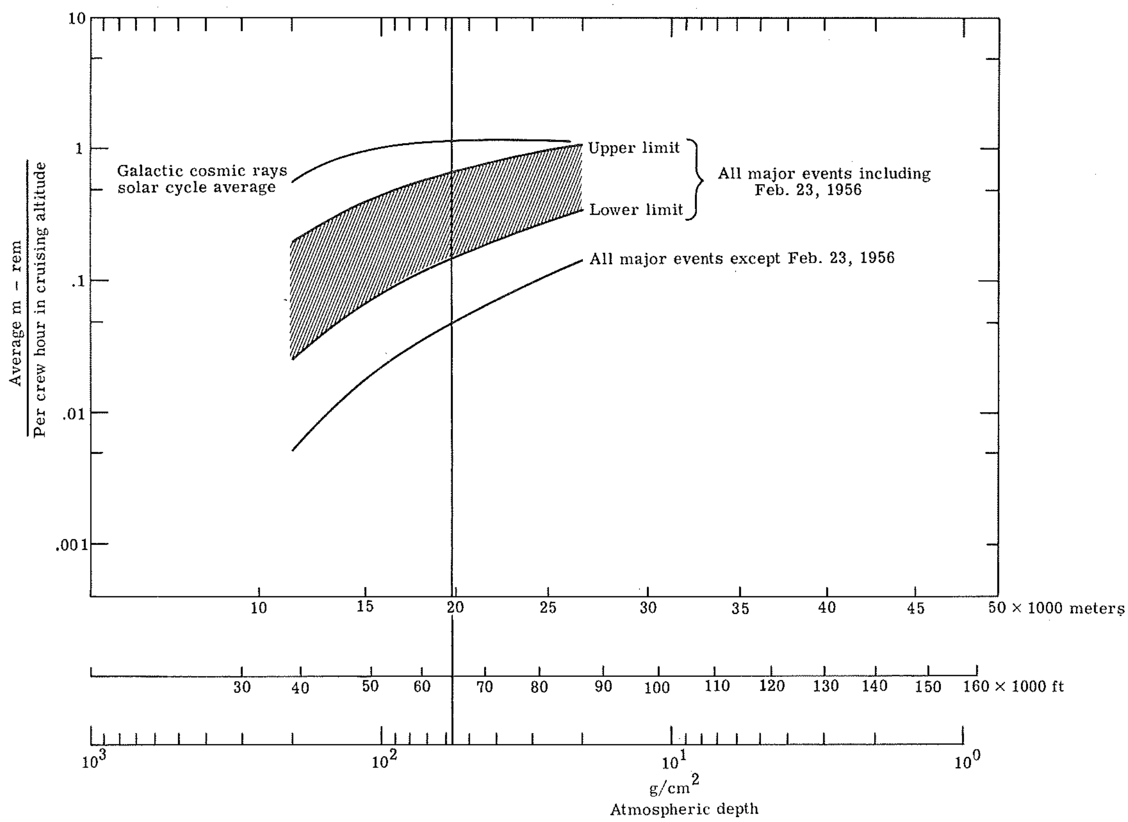

Figure 6.- Average dose equivalent from Solar Cosmic Rays received by the crew having encountered the major events of cycle 19, in comparison to Galactic Cosmic Ray dose equivalent.

Figure 6 indicates that the major solar events of cycle 19 except February 1956 contribute only 1/3 to 1/14 to the total average dose rate of 0.14 to 0.65 m rem/hr at 65,000 feet altitude (dependent on choice of lower or upper limit of the February 1956 spectrum).

In addition to the Solar Cosmic Ray dose rate for cycle 19, the average dose per flight hour in altitude from Galactic Cosmic Rays is indicated in figure 6. It appears that the exposure from Solar Cosmic Rays during the highly active cycle 19 would have been lower by a factor of 1.7 to 7 (dependent on choice of lower or upper limit for February 1956) than the exposure from Gal. C.R. over the solar cycle.

The Solar Cosmic Ray contribution may increase by maximum 0.05 m rem per altitude hour, if the more frequent events of moderate intensity of cycle 19 (as those of high and medium energy of September 3, 1960, and August 12 and 18, respectively) are added, which penetrate deeper than previously assumed. Obviously, this would not change the conclusion, that the contribution from all solar events is smaller than that from Galactic Cosmic Rays.

3. Exposure of passengers from Solar Cosmic Rays

The maximum exposure of passengers to Solar Cosmic Rays would have been the same as that for the crew, if the traveller would have commuted with the same frequency as the crew on the same high latitude routes. In ten years of cycle 19 the exposure would have been $0.65 \times 4800 = 3.1$ rem; that is, still only 0.31 rem/year or 60 percent of the Maximum Permissible Dose rate for the general population of 0.5 rem/year. Since the galactic cosmic ray dose equivalent has to be added, the traveller would belong to the category of radiation workers as the crew. This is considered of no genetic or somatic significance, if the dose is evenly distributed over this period.

The concern might be centered on the fact, that the main part of the exposure would have occurred in a very short time, that is in the 1 to 2 hours of passage through the maximum phase of the February 1956 event. As seen in figure 5 the total body dose equivalent would have been about 0.5 - 3 rem/hr. Such exposure without reason may be considered not permissible for pregnant occupants because of the probability of damage in the early stages of development.

The effectiveness of evasion measures as descent to lower altitude in case a high energy event as that of February 1956 is encountered might be considered.

Figure 5 indicates, the dose equivalent at descent from 65,000 to 30,000 feet decreases as follows:

Altitude	ft km	65,000 20	50,000 15	40,000 12	30,000 9
Dose equivalent in rem/hr					
Upper limit Feb. 56		2.9	1.8	1.	0.45
Lower limit Feb. 56		0.45	0.2	0.1	0.025

The descent to 50,000 feet would reduce the dose rate by a factor of about 2 only; for 30,000 feet this factor is 6.5 or 11, respectively.

IV. Comparison of exposure of crew and passengers inferred for solar cycle 19 with Maximum Permissible Dose Equivalents (MPD) Established by the ICRP

In Table I the Maximum Permissible Dose Equivalents for radiation workers and individuals of the general population may be recalled.

In Table II the dose equivalents produced by Galactic Cosmic Rays and Solar Cosmic Rays averaged over solar cycle 19 in high latitudes and SST altitude, as presented before are summarized and expressed in percent of MPD's. For the February 1956 solar event the upper limit of calculated dose rate of 3 rem/hr is assumed in the table and an encounter for 1 hour. The energy spectra during the maximum phase of this event are not sufficiently known and the dose rate may have been only 1/3 or less of this value. On the other hand, without evation measures the encounter may have lasted for several hours.

Since the exposure of the crew would have been only $\leq$20% of the MPD for radiation workers with regard to exposure of the male crew there is no interference with the recommendation of the ICRP; even the exposure is higher than actual exposure for 90% of the radiation workers in the nuclear industry (ref. 23).

Attention must be given to the fact that the by far largest part of the contribution of solar cosmic rays is due to one giant event and would be accumulated in a very short time; that is, in about 1-2 hours. A total body dose of 0.5 - 3 rem/hr as at February 23, 1956, should not be permissible for pregnant occupants and even children. Besides due to probable development damage in this case the possibility of such exposure by solar cosmic rays could lead to forensic consequencies, if no protective measures or proof is provided, that the exposure did not surpass accepted levels.

It may be emphasized that only one such intense, high energy event occurred during the $10\frac{1}{2}$ years of cycle 19. Events comparable in energy, apparently of lower intensity occurred since their discovery in 1942, in 1946, and 1949 (data, see ref. 6). Since the present cycle seems less active than cycle 19 no such event as February 1956 may encounter the earth until 1975 or even through the next decades. On the other hand, the possibility of an event of even larger size can not be excluded, even though it is considered to occur by an order of magnitude less frequent.

TABLE I

M.P.D.'S (MAX. PERMISSIBLE DOSES)

RADIATION WORKERS & POPULATION

Type of exposure	Condition	Dose, rem
Radiation worker: (a) Whole body, head and trunk, active blood forming organs, gonads, or lens of eye	Accumulated dose	5 times number of years beyond age 18
	$\left(\frac{5\text{ rem}}{\text{year}} = \frac{100\text{ mrem}}{\text{week}} = \frac{15\text{ mrem}}{\text{day}} = \frac{0.625\text{ mrem}}{\text{hour}}\right)$	
(b) Bone	Body burden	0.1 microgram of radium 226 or its biological equivalent
Population: (a) Individual	Year	0.5 (whole body)
(b) Average	30 years	5 (gonads)

TABLE II

AVERAGE DOSES OVER SOLAR CYCLE 19 $\left(10\frac{1}{2}\text{ YEARS}\right)$ IN 65,000 FT ALTITUDE,

MAXIMUM VALUES (MAGNETIC LATITUDES >55°)

		EXPOSURE
CREW:	Galactic C.R.	≈1.2 m-rem/hr.
	Solar C. R. (without precautions)	≈0.7 m-rem/hr.
		1.9 m-rem/hr.
at 10 hours/week flight duty in SST altitude 19 m-rem/week = 19% of MPD for radiation workers (5 rem/year)		
PASSENGERS:	Galactic C.R.	EXPOSURE
	At one round trip per year	Negligible
Only few individuals	At 1/10 the flight time of the crew, ≈ 4 flights per month	0.6 rem/10 yrs. (12% of MPD 0.5 rem/year)
	Solar C.R.	
Without evasion measures on February 23, 1956	Max.: 0.5 - 3.5 rem in 10yrs. (≈10- 50% of MPD for 10 yrs. in a few hours)	0.5-3.5 rem/10 yrs. (10- 67% MPD/10 yrs.)
	Min.: ≈ 0	≈0
		≈0-3.6 rem/10 yrs. (≈0-75% of MPD 10/yrs)

V. Summary on Dose Equivalents as Function of Altitude in High Latitudes Relevant to Commercial SST-Operations, and Precaution Measures to Minimize Implications

Galactic Cosmic Ray dose equivalents in high latitudes and in the altitude range 200 - 30 mb (39 - 68,000 ft, 13 - 21 km) are estimated on the basis of energetic neutron, tissue ionization, and star measurements. These former measurements were made from 1965-68 during the first 4 years of solar modulation of the new cycle. By extrapolating to the entire solar cycle, in SST - altitudes (65,000 ft.) and magnetic latitudes >60^{o} - an average of 1.2 mrem/hr is obtained. At 10 hours/week in cruising altitude, the exposure of the crew would be in the average 12% of the MPD for radiation workers, on high latitude routes. In latitudes below λmagn = 40^{o} it would be about 1/2 or less. If other than Galactic Cosmic Radiations (e.g. Solar Cosmic Radiations) can be avoided there is seen no interference with the ICRP regulations for radiation workers also not for stewardesses or pregnant occupants, except for the effects of heavy primaries or energetic heavy ions, which are estimated practically negligible in these altitudes by experts (ref. , H. Schaefer). The same author emphasizes, that the exposure of 12% of the crew due to Galactic Cosmic Rays is still more than the actual exposure for 90% of the Radiation workers in U.S.A. who receive less than 10% of the MPD.

Measurements during Sol. C.R. events of the neutron component succeeded only in one case (during the late phase of the low energy and intensity event Nov. 18, 1968). Several years will be needed, because of the great variety of spectra which were observed and low frequency of significant events, to check the dose estimates for earlier observed giant and major events experimentally.

To improve early and rough estimates for high energy events such as the February 23, 1956 event, which are considered the only events of significance for commercial SST-flights, a Monte Carlo code was developed which allows to calculate the nuclear cascade development produced by primary protons up to 10 GeV. Although these calculations do not lead to new conclusions, they confirm earlier estimates on the high side and bring to light the energetic secondary neutrons as the principal producer of further secondaries and carrier of the biological dose deep into the atmosphere, especially for Solar Cosmic Rays.

Relevant conclusions are:

1. In the early phase of the February 1956 event 0.5 - 3 rem/hr would have been encountered in high latitudes, and in the part of the fuselage not protected by fuel in the wings by a factor ≈1.5 more. All other extreme events of the highly active cycle 19 produced only doses of <10 to max 50 mrem/hr and are considered as of no significance for commercial SST-flights.

2. Evasion measures as descent to 40,000 or 30,000 feet would have reduced the dose rate in case of February 1956 by a factor of at least 3 and 6.5, respectively.

Such high energy events of large intensity are very rare, about 1 to 2 per 11 year solar cycle as so far observed since 1942. The observed giant events in previous solar cycles were probably of lower intensity than the February 1956 event. On the other hand, events of even higher intensity than the February 1956 event can not be excluded, although they should be even less frequent. Any events with considerable intensity in the multi-GeV range are not considered negligible, because of implications for pregnant occupants.

Evasion measures as descent to subsonic altitude using the considerable thicker air layer above the airplane as shield (≥ 200 g/cm^2), appear as an effective means to avoid or minimize implications on high latitude routes. On equatorial routes the exposure is estimated to be negligible.

As implemented by the British and French Ministries of Aviation for the Concord and considered by FAA, onboard instruments which indicate the dose equivalent including that of energetic neutrons would not only indicate action levels, they might be seen also as an adequate means to avoid costly and unnecessary evation measures at false alarms. Solar forecast and monitoring centers on the ground cannot, at this time, predict the energy spectra of solar events or the energetic events, which are of significance for the SST. These are only very few under relatively frequent, however, insignificant low and medium energy events (in solar cycle 19 about 60). Because of the difficulty in forecasting solar particle events, many more false alarms might be given. Measurements on the ground or in satellites would also not necessarily allow to derive the right dose values at the location of the SST, since in the early most important phase of the energetic events, the particle flux is mainly limited to impact zones. Forecast centers will of course be able to consult if an event is already in progress before take off.

The onboard instruments may also be considered as a means to void unjustified claims, in providing proof, that the exposure did not surpass accepted levels.

Without evasion measures the dose equivalent from both the galactic and solar cosmic rays for the crew would have been $\approx$20% of the MPD for radiation workers (5 rem/year), for solar cycle 19 on high latitude routes. Avoiding the February 1956 event, the exposure is estimated to have been in the order of 13%, which is close to the MPD for individuals of the general population (0.5 rem/year). The latter percentages varies proportionally if in the average more or less than 10 crew hours/week in cruising altitude are assigned.

It is intended to continue the measuring program of NASA not only to confirm the theoretical calculations on solar events, but also to investigate other radiations, as suspected energetic neutron from the sun, and relativistic electron events (REP's) and Aurora.

The above considerations and conclusions are those of the authors, on the basis of limited knowledge on possible new assessments of the biological effectiveness of the radiation components involved.

APPENDIX I

Measurements of Biologically Important Radiation Components in SST Altitudes Produced by G a l a c t i c Cosmic Rays, August 1965 to July 1967.

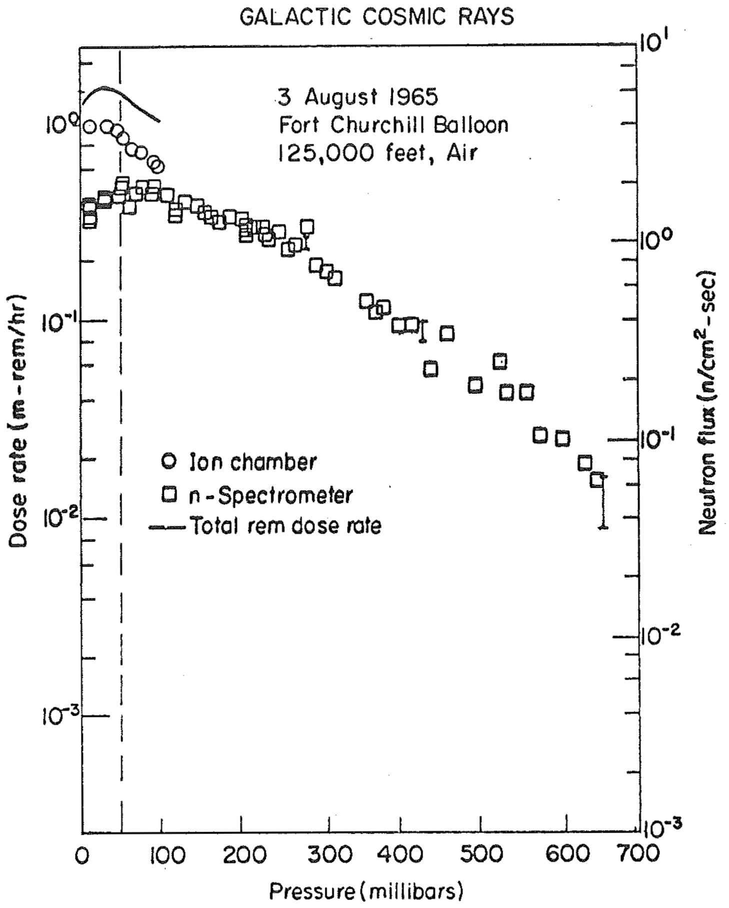

Figure 7.- Galactic Cosmic Ray maximum 1965 (one year after sunspot minimum). Neutron fluxes (right scale) and equivalent dose rates in high latitudes (Fort Churchill $\lambda_{magn} = 69^{o}$) as function of altitude.

The equivalent dose rate is composed of two parts: the ionization dose rate measured in a ion chamber in m rad/hr and the neutron equivalent dose rate. The latter is obtained by extrapolating the n-flux ($E > 1$ Mev) and spectrum 1 - 10 Mev measured in the n-spectrometer to lower energies (≥ 0.1 Mev) using the spectral shape ref. a, fig. 6, 50 g/cm^2 atmospheric depths and multiplying the obtained energy-dependent fluxes with the

[a]H. W. Patterson, W. N. Hess, B. J. Moyer, and R. W. Wallace, Health Physics 2, 69 (1959), and R. W. Wallace personal communication.

flux to dose conversion and RBE factors for monoenergetic neutrons given by W. S. Synder and J. Neufeld.* Using the spectral shape for 60, 40, 20 g/cm^2 atmospheric depths given by W. H. Hess, E. H. Canfield, and R. E. Lingenfelter, (G. R. Vol. 66, March 1961, Pp. 666, Fig. 1) results in only a 7 percent lower combined dose rate equivalent. The theoretical estimates of the absolute values of neutron fluxes greater than 1 Mev differ substantially from these measured values.

As combined dose equivalent one obtains 1.5 m rem/hr in SST altitudes which is within the error limits in agreement with the value in figure 1 if the damage dose of high energy neutrons ($E > 10$ MeV) and charged particle produced stars are subtracted.

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*U.S. Department of Commerce, Handbook 63 "Protection Against Neutron Radiation Up to 30 Million Electron Volts", Nov. 1957, Page 7, Fig. I.

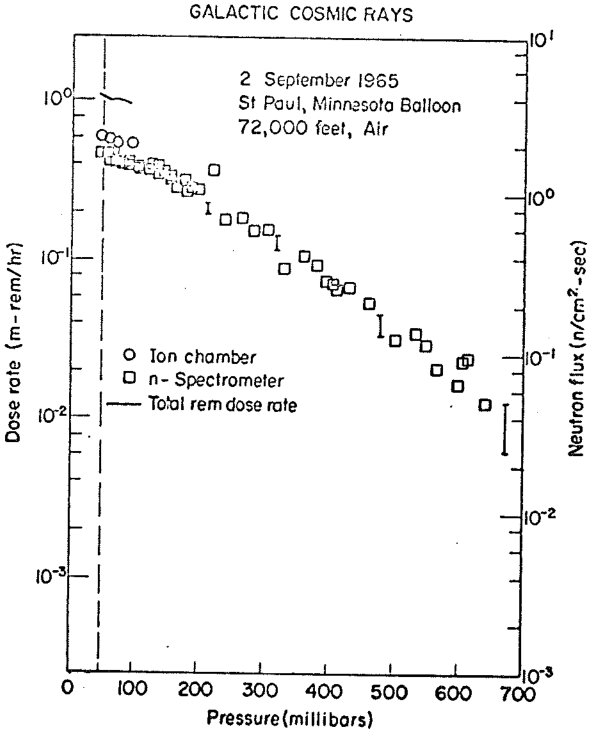

Figure 8.- Galactic Cosmic Ray **Maximum**, (September 1965), as in Figure 7. Neutron flux greater than 1 Mev and equivalent dose rate (Ion chamber rad dose + n-equivalent) above Minnesota at 14° lower magnetic latitude ($\lambda_{magn} = 55^{\circ}$) . The combined equivalent dose rate in 72,000 feet (22 km) altitude is reduced by 27 percent at this lower magnetic latitude. The neutron equivalent is nearly the same as in Figure 7. The decrease is mainly due to the decrease of charged particles (Ion chamber).

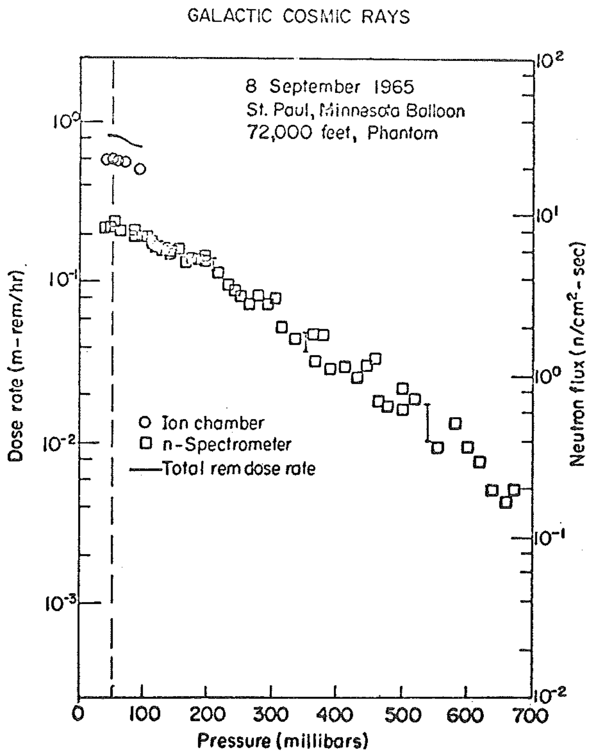

Figure 9.- Galactic Cosmic Ray Maximum (1965). Minnesota ($\lambda_{magn} = 55^{o}$). In the flights, Figures 7 and 8, the sensors were only lightly shielded (less than 1 g/cm^2 Fiberglas and foam). In this flight the sensors are surrounded by tissue equivalent material (including Calcium) of about 15 g/cm^2 thickness, measuring approximately the fluxes and doses in the center of the human body.

The combined dose equivalent within the phantom is only 25 percent lower than within light shielding. The ion chamber dose remains nearly the same. The flux of the biologically important energetic neutrons is reduced by the moderating effect of the hydrogen-containing phantom, which supersedes the neutron production in calcium and other elements of mass numbers > 1. The neutron spectrum was found to be flatter than without phantom.

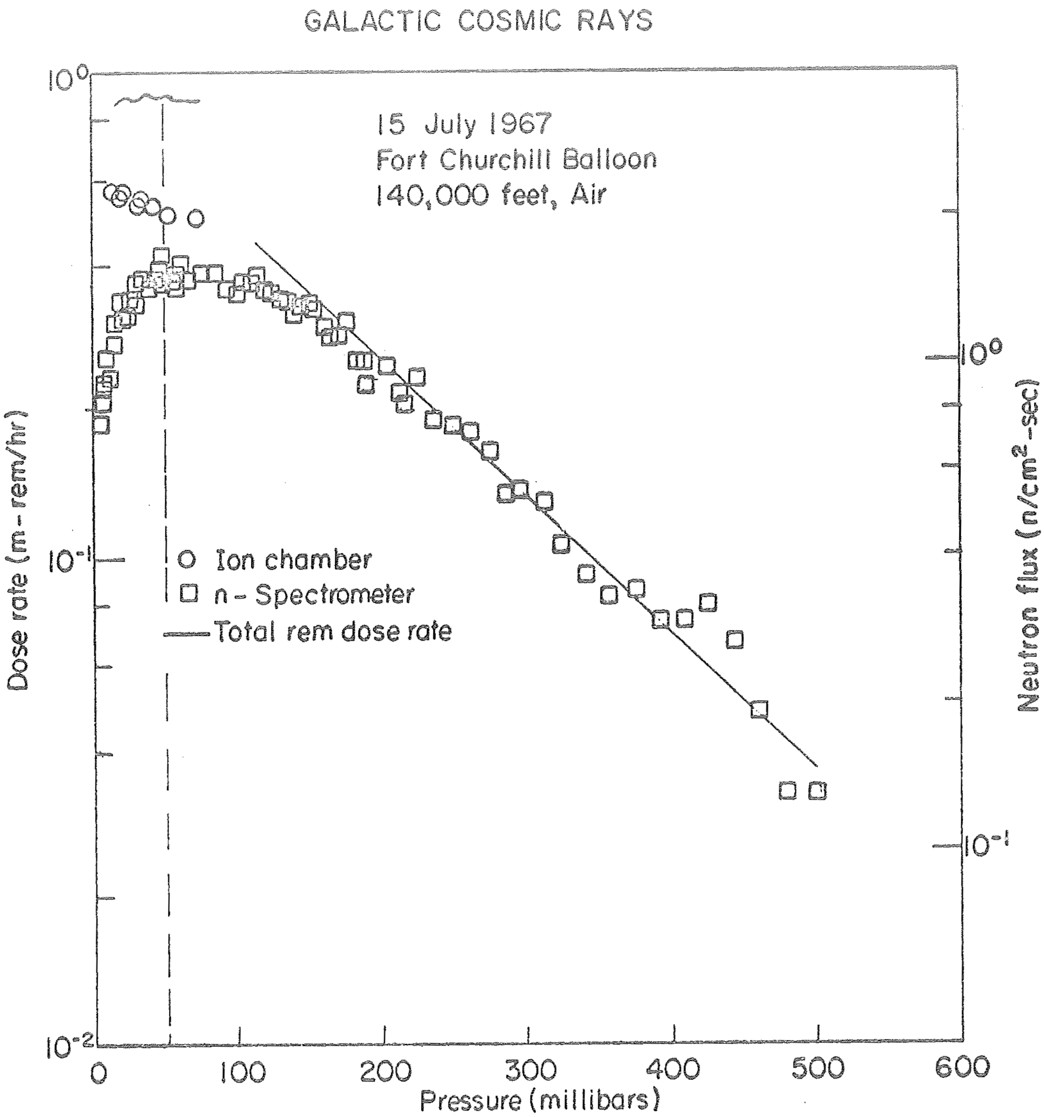

Figure 10.- Galactic Cosmic Rays (July 1967) 2 years after Galactic Cosmic Ray Maximum, Fort Churchill ($\lambda_{magn} = 69^o$); compare to Figure 7.

The equivalent dose rate measured in lightly shielded sensors is decreasing with increasing solar activity, i.e. decreasing Galactic Cosmic Ray intensity. The dose rate equivalent decreased by 40 percent in the 2 years since 1965 (1.5 m rem/hr) to 0.9 m rem/hr. The decrease is mainly due to decrease in direct ionizing particles (Ion chamber), the decrease in neutrons is only 27 percent.

SUMMARY

As the main results of these measurements are considered the absolute values of energetic neutron fluxes which were considerably in doubt, and the slower decrease of the neutron equivalent with latitude and altitude than that of the Ion chamber dose rate produced by charged particles. An upper limit for the combined dose equivalent appears to be approximately 1.5 m rem/hr ±10 percent, not accounting for changes produced by the SST airplanes masses (≅ 300 T) and shielding.

Besides with B-707 in subsonic altitudes during the earth orbiting flight over both poles in November 1965, latitude scans were made with U-II in 1967 and with B-57F in 1968 in supersonic altitudes. At balloon flights floating for 15-24 hours in SST altitudes large nuclear emulsion packages were carried, in which heavy primary thin down hits are recorded. The results will be given at a later date.

APPENDIX II

Transport and Dose Equivalent Calculation for Primary Protons Up to 10 GeV Energy Penetrating Through the Atmosphere

By John W. Wilson

INTRODUCTION

Measurements of the biologically effective radiation components produced by the galactic cosmic rays within the atmosphere, from which equivalent doses are calculated, are presented in Section II. The corresponding data for solar cosmic rays are scant and only reasonable estimates of the primary particle flux spectra are known for a dozen or so such events. Thus, for the energetic solar proton events which have occurred over the last two solar cycles, one must rely on transport calculations to determine flux spectra of the various components (e.g., p, n, π^+, π^0, π^-, γ . . .) in order that dose estimates can be made.

Dose equivalent estimates using transport calculations with nuclear interactions have been made since 1962 in Shielding studies by Kinney, Alsmiller, Irving, and Moran (refs. 24, 25, and 26) and with special application to SST by Curtis (1965, ref. 7) and Leimdorfer et al. (1966, ref. 9). These calculations are uncertain for high energy events since the cross sections at that time were known only to about 450 MeV. In addition to this limitation, the calculations of Curtis used the straight-ahead approximation and considered only to the first generation of particles. The consideration of first generation only will be questionably adequate after two mean free paths. For isotropic incidence, the angle-averaged mean free path is only 35 gm/cm^2 which is well above SST altitudes. For instance, the well known neutron maximum is formed from neutrons which are two and three generations removed from the high energy primary radiation incident on top of the atmosphere.

The Transport Code

The transport code is a set of computer programs written for the CDC-6600 computer. These programs record the history of each incident particle and its progeny until they are stopped, absorbed, or thermalized. An analysis program then reads the history tapes and compiles statistics on the fate of each generation of particles. For example, the statistics compiled for this study are neutron and proton differential flux spectra at various altitudes.

The transport program for energies below 400 MeV was written by Leimdorfer et al. and is described in reference 27. This program was extended to the GeV range by NASA-Langley personnel. The basic structure of the program is the same as that in reference 27 with allowance for the transport of pions.

The high energy nuclear interaction data was taken from Bertini (1967, ref. 28). This reference contains data for protons of incident energies of 0.75, 1, and 2 GeV and for neutrons of incident energy of 1 GeV on the elements O^{16}, Al^{27}, and Pb^{207}. The data for neutrons at energies of 0.75, 1, and 2 GeV on O^{16} is found from the proton data by exact SU(2) symmetry and on Al^{27} by an approximate SU(2) scheme. The cross sections, multiplicities, energy-angle distributions found for neutrons by using SU(2) agreed to within 10 percent with the neutron data of reference 28 at 1 GeV. This allowed us not only to complete the interaction data for neutrons to 2 GeV but also showed that the Bertini calculations are consistent with this basic symmetry principle of strong interactions.

The range of energy for which nuclear interaction data is known (~2 GeV) is not sufficient for such events as that which occurred on February 23, 1956 or for galactic cosmic rays. An examination of the low energy neutron specific yield functions (ref. 29) indicates that the energy dependence of the primaries in the GeV range only slightly affects the secondary nucleon yields. Since the nucleon component was of prime interest it was assumed that multiplicities and energy-angle distributions (normalized to the incident energy) did not change from 2 through 10 GeV. The pion-component will of course not be correct at the high energy end since the onset of diffraction production is ignored. The pions are assumed not to have nuclear interactions since their mean free path to decay is much smaller than their mean free path to nuclear interaction at high altitudes.

The Atmosphere Model

The model used for the atmosphere was that of an infinite layer of air of uniform density. The radiation was assumed to be isotropic from the upper hemisphere. The transport was done without the presence of tissue. Thus, it was assumed that the tissue did not disturb the radiation field to any large degree. This seems reasonable since the penumbra effect would completely overcast the shadow of even an entire airplane. The length of the airplane, ~100 m, is small compared to the mean free path which is greater than 1 km at SST altitudes.

The model used by Curtis is not known. The model of Leimdorfer et al. was to represent the tissue at altitude by an infinite slab of tissue of thickness 30 gm/cm^2.

The transport calculations were carried out for 12,500 protons uniformly distributed over 25 incident energy groups between 0.1 and 10 GeV. The final particle flux spectra were compiled from approximately 4 million particle events including as many as 12 generations removed from the incident primaries.

Dose Estimates

The flux spectra obtained from the transport calculations was transcribed to dose using current to dose conversion factors. The factors for protons were calculated below 60 MeV assuming no nuclear interactions. The data for protons from 60 to 400 MeV was taken from Turner et al. (1964, ref. 19). The rad dose conversion factors above 400 MeV without nuclear interactions were found constant and were equal to the rad dose conversion of reference 19 at 400 MeV. The rem dose (equivalent) conversion above 400 MeV was found by using the average QF of 1.4 of Turner et al. computed at 400 MeV with nuclear interactions. The neutron current to dose conversion factors were taken from Irving et al. (1967, ref. 18) and Kinney and Zerby (1964, ref. 17). All of the above conversion factors include the nuclear star dose equivalent from protons and neutrons.

The dose equivalent due to all particles other than nucleons (e.g.; pions, electrons, gammas) have been neglected. Thus, the rad dose obtained will be too low by possibly 20 to 30 percent. The rem dose is not greatly affected due to the low biological importance of these other sources of radiation.

DISCUSSION

As is the case with any calculation based on a theoretical model, one is faced with the ultimate task of evaluating the essential validity of the calculations. The ultimate confirmation of the transport calculations lies in the comparison with experimental measurement. The only such comparison to be made at this time is with the dose measurements for galactic cosmic rays. First we shall discuss the limitations of these comparisons.

The galactic cosmic rays are composed principally of protons and heavier nuclei (most of which are α's). Of all nucleons incident on the top of the atmosphere, approximately 60% are free protons and the remaining 40% are neutrons and protons in bound states. The energy spectra per nucleon for both are about the same and approximately 90% of all nucleons have energies less than 10 GeV. The heavy nuclei incident on top of the atmosphere loose energy to ionization at a faster rate than protons due to both their larger mass and greater charge. The nucleons arriving in bound states cannot be as prolific in nuclear interactions as free nucleons. It appears also reasonable to assume that fragmentation occurs to a larger extent in the heavy-heavy interactions. In other words, the dose contributed by the heavy component of the galactic cosmic rays is confined mainly to the upper atmosphere. The characteristics to be expected from the transport calculations for galactic protons are as follows: (a) the dose rates should form a maximum (especially during solar maximum) at or above 58 gm/cm^2 which is largely coincident with the neutron maximum, (b) the ratio of the measured dose to the dose calculated for galactic protons should be less than 1.66, (c) this ratio should approach unity deep in the atmosphere. The calculated dose rates exhibit these features as seen in figure 5.

The results of the solar flare calculations are compared with calculations based on the work of Leimdorfer et al (ref. 9) and calculations neglecting nuclear interactions (ref. 11). At altitudes where the primary particles can penetrate, the agreement between the three calculations is good. For low energy events such as the 16:03 event, meaningful dose estimates can be made only by accounting for nuclear interactions. In particular, large numbers of energetic neutrons are produced which penetrate deep into the atmosphere. For high energy events, such as the Upper Limit of February 23, 1956 the calculations based on the Leimdorfer et al data (ref. 9) is not sufficient at SST altitudes. The reason is that the data of Leimdorfer et al. (this data was not intended for such energetic events) was computed to only 450 MeV incident energies, and the penetration at this energy is far less than the deeply penetrating event of February 23, 1956. Again the importance of the neutron component is evident deep in the atmosphere as noted by the increase in the quality factor (the ratio of rem/rad) at subsonic altitudes.

Acknowledgements

The author wishes to express his gratitude for the many useful discussions with Dr. T. A. Filippas and also the help of Jules J. Lambiotte in making these calculations.

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